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Bit Error Simulation of DQPSK for a Slow Frequency Hopping CDMA System in Mobile Radio Communications

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Abstract: *Spread Spectrum (SS) techniques seem to be an attractive alternative to conventional narrow-band modulation. In this paper a Frequency Hopping (FH) system model based on Slow FH (SFH) is proposed. The hopping pattern is in a pseudo-random manner through a set of completely independent channels. The simulated results of the Bit Error Rate (BER) performance of the system for $\pi/4$ DQPSK modulation in the presence of additive white Gaussian noise (AWGN) and Rayleigh fading, together with Bose-Chaudhuri-Hocquenghem (BCH) coding and interleaving are obtained. Consideration is given to the optimum interleaving size, and the system performance in presence of both synchronous and asynchronous interferers.*

Introduction

The limited amount of frequencies and the ever increasing need for flexible services is a permanent challenge for mobile system designer. SS [1] has inherent advantages such as Code Division Multiple Access (CDMA), robustness against narrow-band interferers and multipath fading. Compared to Direct Sequence (DS) SS, FH has been shown to be able to offer similar advantages to CDMA [2, 3]. Frequency synthesizers are the heart of a FH system, and thus the operational performance of the synthesizers is very crucial in the design of a FH system. Investigation at Bristol into the implementation of a sophisticated synthesizer [4] has shown that, while a base station has no difficulty adopting either SFH or Fast FH (FFH) and a SFH mobile handset is practically feasible in a short time, a FFH mobile handset is dependent on current and future sophisticated digital up/down converters.

FH introduces significant phase variations across the boundary of a hop. To overcome the problems of a coherent FH approach which needs to track the phase continuity between different hop carriers, and also the introduced FH phase nonlinearities, together with the fluctuations of a mobile radio channel, differential detection is considered to be an attractive alternative.

This paper considers the statistics of a frequency hopped channel; following some modification to a randomly hopped channel introduced in [5] the gain obtained by hopping to completely independent channels is illustrated. BCH coding applied to FH [3] combined with short interleaving size for burst error correction is considered. The importance of correct interleaving size is highlighted. A simulation model for considering the effects of synchronous and asynchronous interference is introduced, and the dependency of the system on the hop sequence allocation is investigated.

Communication System Model

Transmission System

A schematic diagram of the transmission FH system for $\pi/4$ DQPSK, with baseband equivalent complex envelope representation, implemented on a SPW^1 time domain simulator is shown in Fig. 1. Two levels of interleaving are used. Firstly the encoded input bits are bit interleaved, so that no two adjacent bits form a symbol. Secondly the bits are block interleaved in order that adjacent symbols are not transmitted in the same hop. The $\pi/4$ DQPSK modulation scheme groups the data bits into symbols that are mapped to the differential phase of the transmitted carrier. The number of bits sent is determined by the required error rate.

An overall raised cosine (RC) filter shared equally at transmitter and receiver (thus square root RC) is implemented. A quaternary symbol rate of 5 kbps is formed from a 10 kbps data rate, and the signals at the output of the filter are affected with the time-varying characteristics of the simulated channel; white Gaussian noise is added to the signal at the output of the channel. The channel is considered to be stationary over two consecutive symbols. Cochannel interference is added to the desired signal at the input of the receiver. The cochannel interference level is set by the ratio of the desired average signal power (C)

[1] SPW is a trademark of $ALTA\ GROUP^{TM}$ of Cadence Design Systems, Inc.

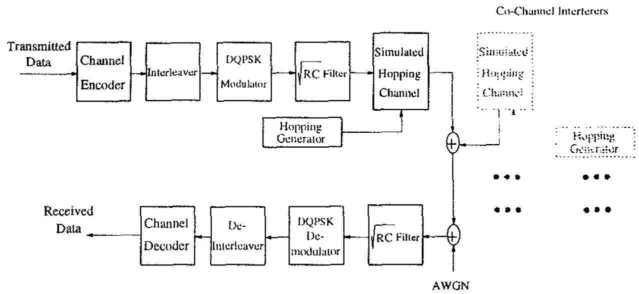

Figure 1: Schematic diagram of the FH system model

to the average interference signal power (I), denoted as (C/I).

Channel

The synthesizer action modulates an already modulated signal by a frequency translation where the carrier frequency is pseudorandomly changed, resulting in a narrowband signal which hops over a wide band of of spectrum. The synthesizer produces a signal $h_T(t)$, consisting of a sequence of tones of duration T_c, written as:

$$h_T(t) = \sum_{n=-\infty}^{\infty} 2p(t - nT_c)\cos(\omega_n t + \phi_n) \qquad (1)$$

where $p(t)$ is a pulse of unit amplitude with duration T_c starting at time zero, and ω_n and ϕ_n are the radian frequency and phase of the n^{th} frequency-hop interval, respectively. The transmitted signal, $s_n(t)$, is the modulated data $m_n(t)$ up-converted by frequency ω_n on each FH chip, written as:

$$s_n(t) = \left[m_n(t) \sum_{n=-\infty}^{\infty} 2p(t - nT_c)\cos(\omega_n t + \phi_n) \right] \qquad (2)$$

Another FH synthesizer at the receiver dehops the received signal $r(t)$ back to its primary modulation format ready for the demodulation process. The synthesizer at the receiver produces the same frequency as that in the transmitter, in order that the $r(t)$ is always brought back to the same IF.

A randomly hopped channel is simulated following the appropriate corrections to the diversity model introduced in [6]. These non-deterministic phase changes at the beginning of the hops ensures a random placement of the signal in and out of the coherence bandwidth of the channel. To have some control on the chosen frequency channel at each hop, a set of completely independent channels were shaped by exact setting of the appropriate phases of each channel. At the beginning of each bin the hopping generator selected a frequency channel according to a psuedorandom selection pattern.

Cochannel interference was considered by allowing other users to use the same set of frequencies, but using an offset version of the same code sequence. Due to consideration of intracell orthogonality all the users in the same cell were synchronised; but to consider the effect of some occasional interference due to allocation of more users than the number of channels, the frequency set was spread out. This results in gaining more channels at the expense of some frequency hits, with synchronous interference hitting the complete hop duration. Users in other cells use the same set of frequency channels, but each cell is completely independent from an adjacent cell in its sequence code, and also in its hopping time. Asynchronous interference in this case is a sum of all asynchronous interferers from adjacent cells.

Receiver

The complex samples at the output of the sample and hold device were processed with a differential phase detector. Taking the real and imaginary components at the output of the detector as decision variables eases the diversity consideration. The gross changes in the signal phase at the end of one hop and start of the next invalidated the assumption of stationary channel made earlier. The approach taken was to insert a reference symbol at the start of each hop frame, to be removed later at the receiver. This implies the more the number of the information symbols, the less overhead in each frame.

Simulation Results

Two different methods are used to simulate the frequency hopped channel. One is based on a random hop, and the other based on a deterministic psuedorandom pattern in which the frequency channels are randomly permutated and updated every arbitrary bin. The *overall* and *instantaneous* statistics of the simulated channel were investigated and are fully explored in [5], where it is shown that, although the cumulative probability of the signal level does not change by the process of hopping, the instantaneous statistics of the channel will change. This results in an increase in level crossing rates, and a decrease in fading durations of the signal level. This is in fact a desirable aspect of a FH system in a fading mobile channel, which indicates a direct relationship between the hopping rate and the time spent in a fade.

Fig. 2 shows the simulated results of the system BER against E_b/N_0 for $\pi/4$ DQPSK with BCH (7,15) coding and a symbol interleaving size of (10×10) under a Rayleigh fading condition of $f_d = 10$ Hz. The uncoded $\pi/4$ DQPSK results, matching the theoretical results of Adachi [7] are also shown for comparison. The coding and interleaving alone does not seem to improve the BER till around E_b/N_0 of 18 dB due to the nature of the slow fading channel. The hopping system, on the other hand, does not need a large interleaving size, and it can be seen that the irreducible

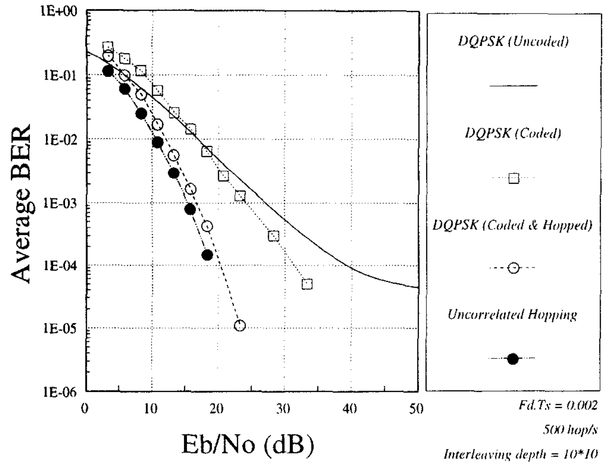

Figure 2: $\pi/4$ DQPSK BER Performance

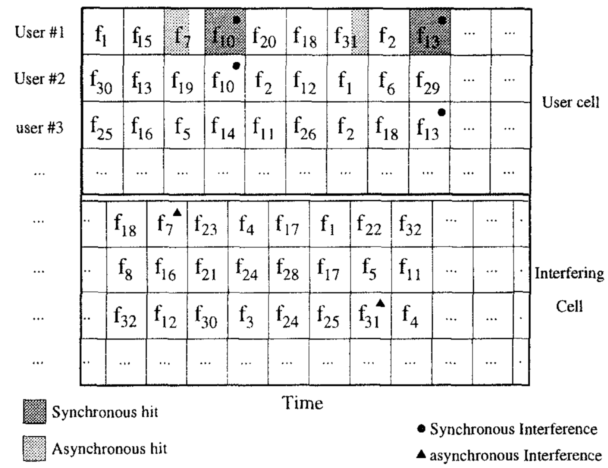

Figure 4: Concept of synch. and asynch. FH hits

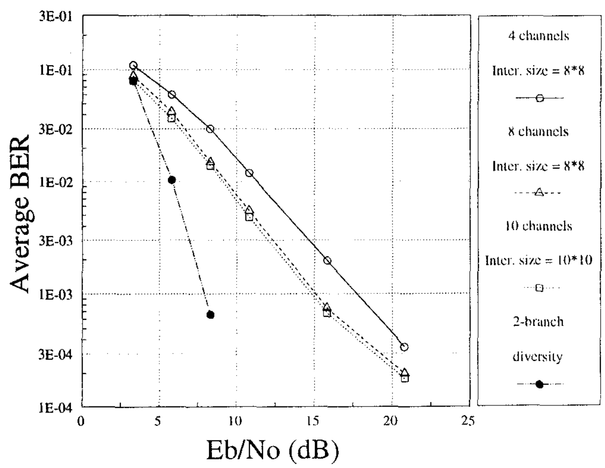

Figure 3: Interleaving, with 2-branch diversity

error floor is well passed. The improvement is obtained by breaking up of the burst errors into different frequency bins. Taking a nominal BER of 10^{-4}, the non-hopped channel has a 10 dB worse performance than the hopping channel. This performance gain is about 15 dB if the hopping channel is compared with the normal $\pi/4$ DQPSK. There is also shown the BER performance of the system using the completely uncorrelated hopped channels, and a further gain of around 1.5 dB is achieved. Hereafter, this second version of the channel is used. It has been shown [5, 8] that using an adequate number of FH channels significantly reduces the BER. Fig. 3 shows that when the number of FH channels are equal to the number of symbols in one interleaving block, no further gain can be achieved by increasing the number of channels. There is also shown a 2-branch post detection space diversity performance, where there is a further gain of approximately 6.5 dB for BER of 10^{-3}

A schematic diagram of the hopped frequency format is illustrated in Fig. 4 where the effect of interference on the intended user is highlighted by the grey areas. To consider the multi-user case, a set of 32 frequency channels was considered. To simulate the effects of interference, a channel was allowed to be used more than once. This simulates a more realistic system where the number of users communicating are more than the number of frequencies, and also considers the effect of fixed-frequency interference. The penalty paid for this is the occasional hits when two users are using the same frequency band. Complete synchronisation is assumed within each cell, so that there is either no hit from a secondary user in the same cell, or the occasional hits are completely synchronised with the hop frames of the desired user. This is here referred to as *synchronous* interference, resulting in frequency hits which affect the whole frame within a hop. Each interference was produced by passing a different random bit stream through a phase shifted version of the same hop code sequence.

Fig. 5 shows the BER results of the system against C/I for different E_b/N_0. The first set of results was obtained for the case of no-noise ($E_b/N_0 = 100$) dB, resulting in an overall 11% frequency hit. This ratio was kept constant for other C/I, and repeated for different E_b/N_0. It clearly indicates the general trend of decrease in BER as C/I is increased. The performance is dependent on E_b/N_0, but as E_b/N_0 increases this dependency decreases such that there is no significant reduction in BER above E_b/N_0 of 30 dB, and the system becomes interference limited. The performance of the system is also dependent on the hopping sequence pattern. Fig. 6 shows this for a no-noise

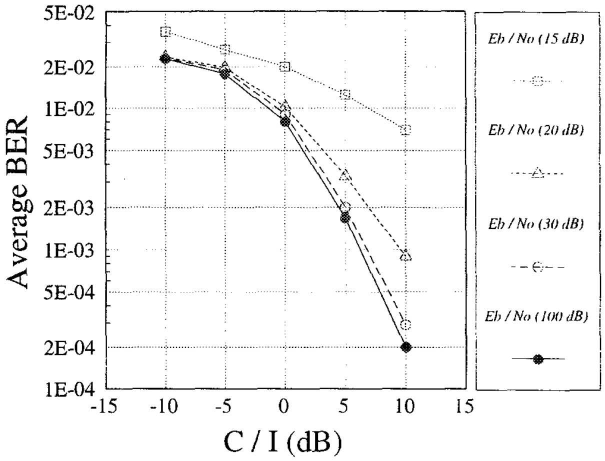

Figure 5: FH under synchronous interference

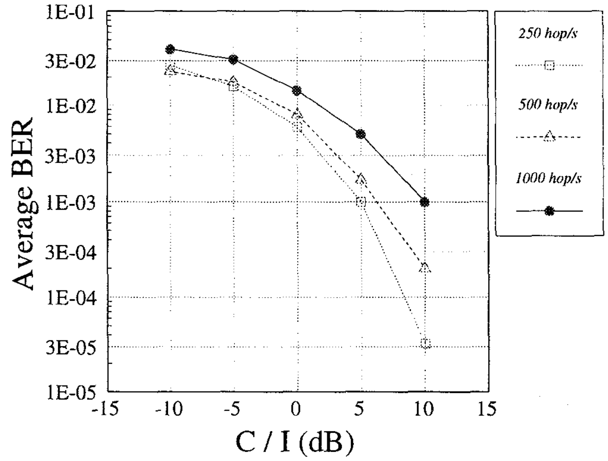

Figure 7: FH performance for different hop rates

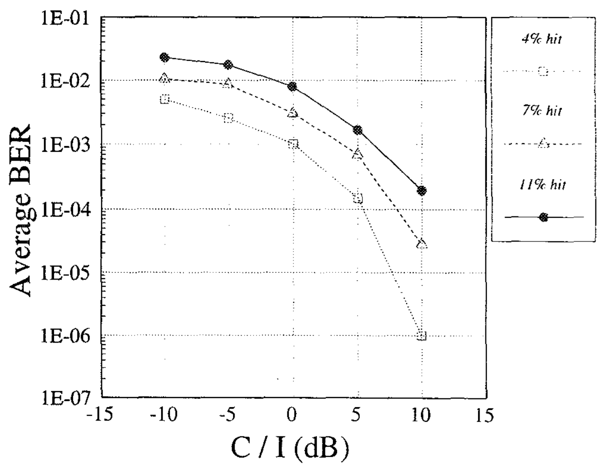

Figure 6: FH BER for various hit percentages

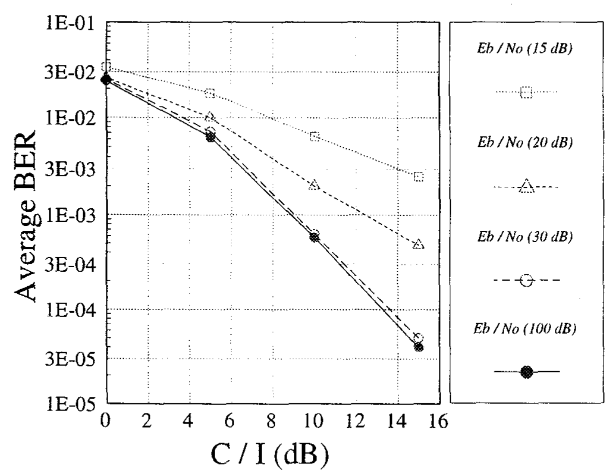

Figure 8: FH under asynchronous. interference

case for 3 different percentages of frequency hits. There is a similar decreasing BER pattern in all cases for up to C/I of 5 dB; thereafter, the difference becomes significant.

The effect of hopping was also investigated, and the results are shown in Fig. 7 where it is evident that if the overall percentage of hits is kept constant, there is a decrease in BER performance for faster hops. This is because, although more hopping channels are used in each unit of time, the overall percentage of hits stays the same; faster hops, however, imply smaller frame blocks and therefore, less overall gain. Here again, the difference in BER performance starts to grow beyond C/I of 5 dB.

The Cochannel interference caused by the asynchronous users in the adjacent cells was modeled by considering six surrounding cells, each being synchronised internally. If the same scenario as that of the user cell is used, each adjacent cell interference has its own internal synchronous hits, in order that its overall interference contribution to the user cell is accounted for. Fig. 4 shows one of the interfering cells, producing frequency hits which are not in time with the hop frame of the user cell. Each adjacent cell is considered to have a different hop sequence code, and a different number of users. The time mismatch for each cell is simulated by allowing an arbitrary hop time lead or lag. This creates the partial hits which only affect some fraction of the hop frames. The BER performance of the system under this kind of interference is presented in Fig. 8, where it can again be seen that the interference limits the BER level not much gain is found beyond E_b/N_0 of 30 dB. The system shows a worse performance when compared to the synchronous interference case, such that for a noise-free case there is 3 times as much error for C/I of 10 dB.

Fig. 9 shows the simulated system capacity for the syn-

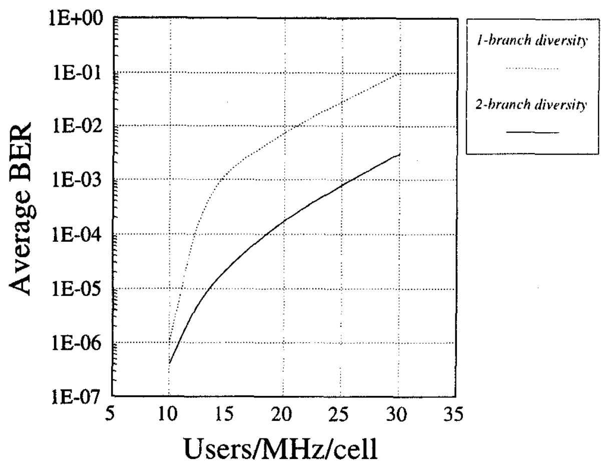

Figure 9: FH capacity consideration

chronous interference with 11% hit, together with the improvement obtained by employing a 2-branch space diversity. For a voice quality BER of 10^{-3}, the tolerance of the system is for up to around 15 users; while this figure increases to 26 when a 2-branch dicersity is used.

Conclusion

The benefit of FH in breaking up the burst errors is highlighted. Two FH channel model were introduced, and it was shown that by using a pseudorandomly hopping independent channel a gain of 1.5 dB is obtained compared with a completely random hopped channel. The optimum interleaving size was shown to be dependent on the number of FH channels and symbols per frame, resulting in best performance when number of FH channels is equal to the maximum number of symbols in one interleaving block, with a further gain of 6.5 dB at BER of 10^{-3} when a 2-branch diversity is used.

The simulation format for synchronous and asynchronous cochannel interference was introduced where all the users in one cell were in complete synchronisation, while other cells had arbitrary lead or lag hop start-time. Other users in the user cell clashed with the whole block of the intended user in the hit bins, while asynchronous interference produced partial clashes. The system showed an interference limited behaviour where further noise reduction beyond 30 dB had not much more improvement effect in both cases. The system BER performance for different percentages of frequency hits was obtained indicating that it is directly related to the code sequence pattern, and that for a given C/I there is an increase in the BER differences, among different hit cases, when the C/I is above 5 dB. The effect of different hopping rates was also investigated showing that although faster hops have less time in fade for each hop duration, but if all users are hopping at the same rate, the total hit percentage stays the same; and slower hops give better performance due to having less overall reference symbols. Finally the system showed a capacity of about 15 users for 10^{-3} BER in a 11% hit synchronous interference, and increasing to 26 for a 2-branch diversity.

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